ANALYSIS OF MUDFLOW DISCHARGE COEFFICIENTS AND OPTIMIZATION OF FLEXIBLE BARRIER DESIGNS UNDER CLIMATE CHANGE

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Abstract. *The increasing frequency of extreme hydrological events in Uzbekistan, driven by climate change and accelerated glacial melting, necessitates the implementation of advanced flood mitigation structures. This study analyzes the efficiency of flexible (elastic) debris flow barriers and proposes their adaptation for the specific orographic conditions of the Tashkent region, particularly the Bostanlyk district. By evaluating the relationship between the probability of exceedance (P) and the discharge coefficient (A), the research demonstrates that traditional rigid dams often fail to dissipate the dynamic energy of flash floods. The paper provides scientific recommendations for improving flexible barrier designs by integrating triangular prism deflectors and an elastic cable network. These enhancements are aimed at creating a "launch-ramp" effect to redistribute impact forces. The findings offer a technical basis for modernizing Uzbekistan's flood management infrastructure, emphasizing material durability (B25 concrete, W8 waterproofing) and structural elasticity as key factors for regional hydrological security.*

Keywords: *Mudflow flow, climate change, elastic barrier systems, hydrodynamics, structural improvement, energy dissipation, point foundation, filtration mechanism, engineering protection.*

INTRODUCTION

In recent years, a significant increase has been observed worldwide in the occurrence of large-scale natural and man-made emergency situations with severe consequences. This trend has led to a growing number of people being left without shelter, an increase in premature mortality, and substantial economic losses. Consequently, there is a pressing need to ensure effective protection of the population and territories during such emergencies, as well as efficient management of the forces and resources involved in response operations. Special importance is attached to the advance training of managerial and operational personnel of governing bodies responsible for emergency protection, mitigation of consequences, and provision of essential living conditions for the affected population. In recent years, emergency situations occurring within the territory of the republic have consisted of 58.9% man-made and 41.1% natural events. Given their scale and level of damage, man-made emergencies demonstrate higher impact indicators, necessitating the implementation of targeted risk reduction measures. In this context, particular attention is paid to improving the effectiveness of the state emergency prevention and response system, including the management bodies, forces, and resources involved in mitigating the consequences of local and regional emergency situations.

In accordance with the fundamental principles of emergency protection in the republic-namely humanitarianism, the priority of human life and health, and the effective organization and implementation of emergency protection measures-systematic actions aligned with the administrative reforms of the "New Uzbekistan" framework are being implemented. Within this context, the state system for emergency prevention and response places emphasis on conducting scientific research aimed at enhancing and developing the competencies, skills, and managerial capacities of leaders of governing bodies responsible for the management of forces and resources during emergency situations. To address these objectives, particular importance is attached to the development of protection algorithms and models based on the identification of potential emergency hazards and contributing factors. This approach is intended to improve the operational effectiveness of existing emergency management authorities, ensure the protection of the population and territories during emergency situations, and optimize the balance between forces and resources involved in emergency prevention, response, and consequence mitigation.

EXPERIMENTAL RESEARCH

The Resolution of the President of the Republic of Uzbekistan No. PQ-311 dated October 20, 2025, *"On Measures for the Digitalization of the Emergency Protection Sector and the Development of Scientific and Innovative Activities,"* together with Presidential Decree No. PF-60 dated January 28, 2022, which approved the *"Development Strategy of New Uzbekistan for 2022–2026,"* defines the strengthening of national security and defense capacity as a key priority. In particular, within Goal 92-focused on enhancing national security and implementing an open, pragmatic, and proactive foreign policy-the establishment of an effective system for the prevention and mitigation of emergency situations is identified as a priority direction with clearly defined objectives and tasks. Ensuring the protection of the population and territories of the Republic of Uzbekistan from flood and mudflow hazards, as well as from emergency situations that may arise in reservoirs due to such events, is of critical importance for safeguarding human life and preventing the escalation of emergency impacts. Achieving these objectives requires a scientifically grounded assessment and analysis of hydro meteorological observations to identify areas exposed to mudflow and flood risks, to reveal existing challenges, and to implement an effective system for preventing flood-related emergency situations that may result from potential failures of hydraulic structures and reservoirs.

Regions with High Mudflow Risk Across the Republic

Table 1

Region	**Number of Mudflow Sites**	**Main Hazard Types**	**Historical Peak (Recent Years)**
Namangan	124 ta	Flash mudflows, Kosonsoy basin	July 2021 (Kosonsoy disaster)
Surxondaryo	108 ta	Mudstone-laden mudflows	Spring 2022 (Sherobod, Boysun)
Tashkent Region	95 ta	Glacial and mixed mudflows	March 2023 (Rivers of Chirchiq basin)
Jizzakh	82 ta	Floods resulting from flash flows	April 2022 (Egizbuloq disaster)

Statistical data from countries worldwide indicate a continuous increase in both the frequency and magnitude of natural disasters. Similar trends are also observed within the territory

of the republic, where natural hazards occur with increasing regularity. Analytical assessments reveal that there are 409 rivers and streams across the republic that are exposed to mudflow hazards, with the highest concentration located in specific regions, as presented in Table 1.

On June 9, 2015, in the Beshko‘bi village of Zomin district, Jizzakh region, intense rainfall caused a mudflow that swept away a VAZ-2106 vehicle. Of the five individuals in the vehicle, two lost their lives. On May 15, 2016, in Pop district of Namangan region, a mudflow triggered by heavy rainfall inundated 58 houses in the Kalqurbon mahalla. On May 16 of the same year, subsequent mudflows in the same mahalla resulted in the complete collapse of one house, claiming the lives of three out of four family members residing there. On May 16, 2018, in Chiroqchi district, Qashqadaryo region, intense rainfall caused a mudflow in the Mirzato‘q mahalla, Sariqqamish village, resulting in five fatalities. On May 1, 2020, the breach of six piers of the Sardoba reservoir dam in Sirdaryo region led to the flooding of the Qorqontepa settlement in Sardoba district. In total, 22 settlements across 10 mahallas were affected, damaging 5,388 residential and non-residential structures.

Among these, 1,691 were individual houses;

2,038 were concrete-panel residential buildings;

1,014 were multi-storey apartments;

147 were standard-design houses;

455 were incomplete houses or vacant plots.

Fully destroyed houses numbered 1,640, while 3,003 required major repairs. Furthermore, 108 farms and agricultural enterprises suffered damage to 16,525 hectares of land, including 9,704 hectares of cotton, 6,821 hectares of grain, 231 hectares of vegetables, 1,095 hectares of melons, 14 hectares of potatoes, 154 hectares of orchards, and 83 hectares of vegetable plots within orchards. In addition, 66 km of gas pipelines, 47 gas distribution facilities, and 7,550 household gas cylinders were damaged across 11 settlements in Sardoba, Oqoltin, and Mirzaobod districts. Significant damage also occurred to irrigation infrastructure, including 8.5 km of the “Central Network” canal, 4.5 km of the “Right Network” canal, and 3 km of the “Left Network” canal. These events underscore the increasing hazards in the geotechnosphere and highlight the necessity of constructing additional protective engineering structures to safeguard human settlements and critical infrastructure.

On March 15, 2022, in Baxt settlement of Sirdaryo district, a flood completely rendered two multi-storey residential buildings uninhabitable. On May 4, 2022, in the mountainous areas of Zomin district, Jizzakh region, heavy rainfall caused mudflow events along streams passing through the Peshag‘or, Achchi, Qang‘li, and Shorcha villages. According to the regional Department of Internal Affairs, two individuals stranded by the mudflow were successfully rescued. In response to the flood, 140 rescuers and 8 specialized vehicles from the regional Emergency Situations Department, along with 83 personnel and 25 specialized vehicles from subordinate organizations of the state emergency prevention and response system, were deployed. Teams conducted assessments in streets and residential areas affected by the floodwaters and cleared debris, while accumulated water from courtyards and basements was removed using specialized equipment.

On May 5, 2022, at 23:00, in Uzun district of Surxondaryo region, intense rainfall in mountainous and hilly areas caused the “Orta Ariq” canal, which passes through the “Toshtepa” area of the “22nd Anniversary of Independence” MFY, to overflow. This flooding affected nearly 40 residential houses, gardens, and 15 household plots in the Dehqon mahalla. To ensure the safety

of residents, over 230 individuals from the 40 affected households in Toshtepa village were temporarily relocated to School No. 19 in the district under the coordination of the regional Emergency Situations Department, in cooperation with rescuers, the Ministry of Internal Affairs, the National Guard, and responsible officials from the regional administration. Uzbekistan can thus be considered among countries facing frequent flood risks. Rapid development of mountainous areas has disrupted natural conditions, contributing to the emergence of numerous mudflows. As a result of ecological imbalance, mudflows now occur in locations previously unaffected. Considering existing and potential hazards, alongside a comprehensive approach to planning and design, allows for scientifically justified measures to protect against mudflows. Between 2015 and 2022, a total of 507 mudflow events were recorded across the territory of the republic. The distribution of these events by year is presented as follows.

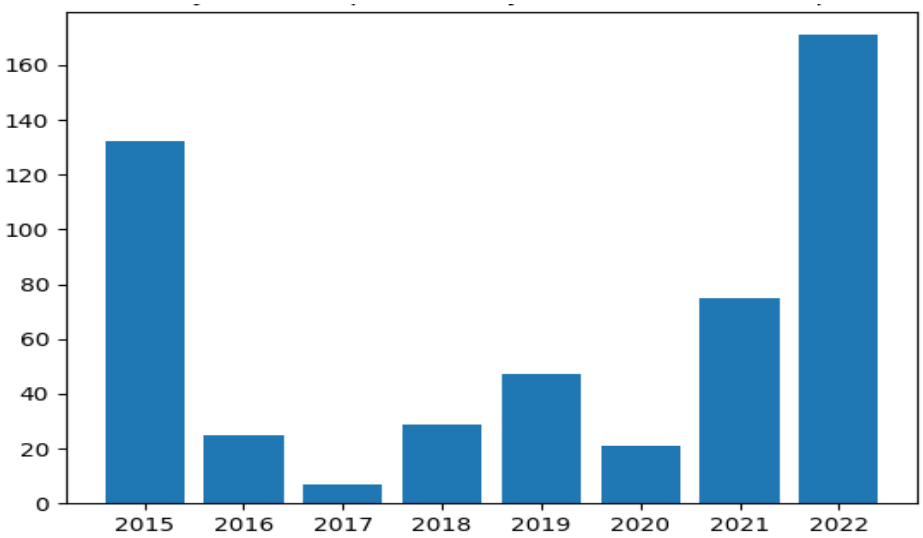


FIGURE 1. Number of flash floods and floods in the Republic from 2015 to 2022 years

The climate of the Republic of Uzbekistan is situated within one of the regions most significantly affected by global warming. According to data from the Agency for Hydrometeorological Services of the Republic of Uzbekistan (Hydromet), the average air temperature in the country has increased by 1.5°C since 1900, which notably exceeds the global average increase of 1.1°C. This warming trend is particularly accelerated in mountainous regions compared to lowlands, reflecting a shift in the vertical temperature gradient. This process leads to an increase in the moisture-holding capacity of the atmosphere. In accordance with the Clausius-Clapeyron equation, for every 1°C increase in temperature, the water vapor holding capacity of the air rises by approximately 7%. Consequently, the immense energy accumulated in the atmosphere manifests as short-duration yet extreme convective rainfall events. An analysis of mudflow and flood occurrences across the republic's territories during the period of 2016–2022 is presented in Figure 2.

The highest incidence of these events was recorded in the Fergana region, accounting for 23.4% of the total cases. This high frequency is attributed to the region's foothill and mountainous relief, the frequent occurrence of short-term intensive precipitation, and the high density of the river and stream network. The Namangan region ranks second, with a 20.0% share of mudflow and flood events. Key risk-amplifying factors in this area include the high concentration of settlements located in the foothills and the rapid rise in water discharge levels. The third-largest share belongs to the Surkhandarya region at 18.9%. The topography of this region is characterized by sharply fragmented relief, where mudflow events are primarily driven by rapid snowmelt and

heavy rainfall during the spring months. In the Tashkent and Kashkadarya regions, these figures stood at 11.8% and 10.8%, respectively. The hazard levels in these regions are further exacerbated by the proximity of flood risks to industrial and infrastructure facilities. Although relatively lower indicators were observed in Jizzakh (6.6%), Navoi (4.74%), and Samarkand (2.63%) regions, mudflow events in these areas can still result in severe damage under specific meteorological conditions.

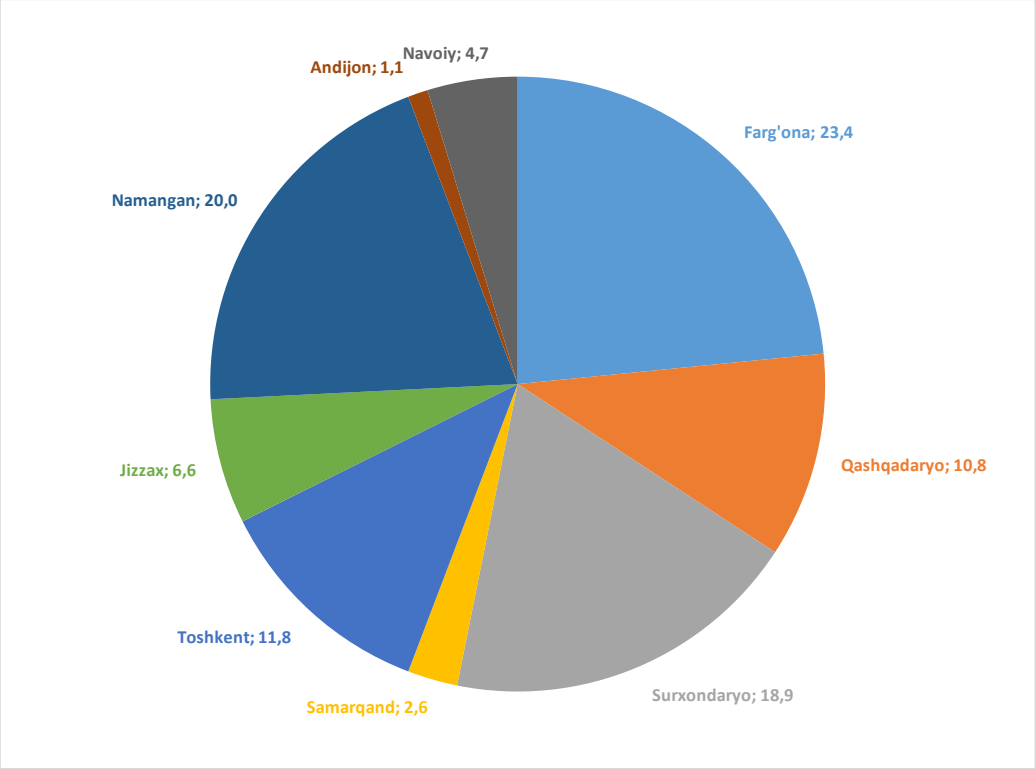


Figure 2. Regional distribution of mudflows and flood events.

The lowest percentage was recorded in the Andijan region, at only 1.05%, where the relatively flat terrain leads to a lower frequency of flood hazards. Extreme rainfall events lead to a sharp increase in water levels, exceeding the capacity of rivers and lakes, subsequently flooding agricultural lands, residential areas, and transport infrastructure. Such disasters result in substantial economic losses, fatalities, and the disruption of vital life-support systems.

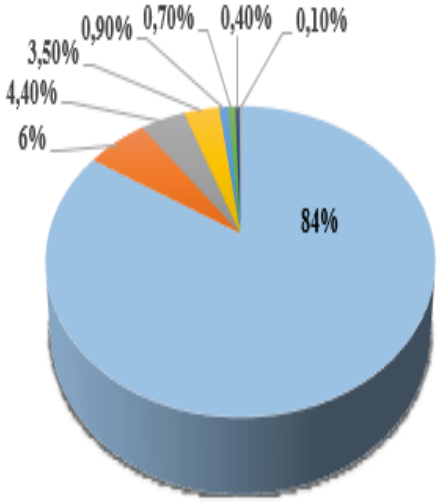
The primary causes of flood occurrences are systematically categorized in Figure 3.

Dynamics of Precipitation and Runoff Patterns

- **Increased Intensity:** Over the past 15 years, the frequency of days with daily precipitation exceeding 30 mm has increased by 15–20%.
- **Seasonal Shifts:** The peak period for mudflow activity, which historically occurred in April and May, has shifted toward late February and March. This phenomenon is driven by the convergence of rapid snowmelt and intensive rainfall, leading to the formation of "mixed-fed mudflows."
- **Localization:** Flood events are increasingly characterized by their extreme speed (flash floods) within small mountain river basins (soys) with catchment areas of up to 50–100 km².

Glacial Degradation and its Hydrological Consequences Uzbekistan's hydrological security is fundamentally linked to the glaciers of the Pskem, Chatkal, Gissar, and Turkestan ranges.

- **Glacial Reserves:** Central Asian glaciers have lost approximately one-third of their total volume over the last 50 years.



Heavy rainfall / Intense precipitation	**84%**
Rapid snowmelt	**6%**
Rain accompanied by hail	**4.40%**
Rain-on-snow events (Combined snowmelt)	**3.50%**
Dam or embankment breach	**0.90%**
Hailfall	**0.70%**
Glacial lake outburst floods (GLOF)	**0.40%**
Other miscellaneous factors	**0.10%**

Figure 3. Causative factors of flood occurrences

- **Hydrological Impact:** Accelerated glacial melting has increased the base flow of mountain rivers. However, this has compromised the static stability of riverbeds, resulting in a 1.2 to 1.4-fold increase in the concentration of solid sediments (stone, sand, and silt) within mudflow mixtures.

Glacial Lake Outburst Floods (GLOFs) Out of more than 800 high-altitude lakes threatening the territory of Uzbekistan, 124 are classified as breakout-prone (moraine-dammed lakes). A breach in these natural dams could trigger the instantaneous release of tens of millions of cubic meters of water-silt mixture, descending to lower altitudes within minutes.

Socio-Economic Impact and Risk Management Approximately 12% of the Republic's territory is situated within high-risk flood zones. These disasters annually inflict severe damage on economic sectors and infrastructure, including agricultural lands, residential settlements, industrial facilities, and irrigation systems. Most tragically, these events result in human fatalities.

- **Vulnerable Populations:** Currently, 4,149 households and 21,426 individuals reside in flood-prone areas, with the highest population density recorded in the Fergana region.
- **Monitoring and Infrastructure:** Within the state system for emergency prevention and response, over 300 observation posts are operational. There are 29 primary mudflow basins identified in Uzbekistan, primarily concentrated in the mountainous provinces of Namangan, Fergana, Surkhandarya, Tashkent, Kashkadarya, and Samarkand.

At present, there are several sites within the study area where peak discharge erosive flows occur multiple times annually. This phenomenon serves as a primary indicator of spatial differentiation in hazard levels. Based on the results of our field scientific research conducted in the mudflow and flood basins of the Bostanlyk district, Tashkent region, we have derived an equation to calculate the slope erosion coefficient as a function of time.

$$E = [0.58 + 1.40(F_1/F_0) \cdot (t/T)0.21], \quad (1)$$

The calculation of the slope erosion coefficient is based on the relationship between the eroded surfaces and the total catchment area over a specific timeframe. The variables are defined as follows:

F_1 – the eroded area within the river basin (km^2);

F_0 – the total surface area of the river basin (km^2);

t – the specific time interval (year);

T – the total duration of the observation period.

Furthermore, the peak discharge value of mudflows from various sources of origin is calculated using the following analytical expression:

$$Q_{\max} = A(34 + 400i)F_0^{0.61} \text{m}^3/\text{s}, \quad (2)$$

The variables within the aforementioned formula are defined as follows:

A – the mudflow discharge coefficient, the values of which vary depending on the probability of exceedance (P%) as detailed in Table 2.

Relationship between the mudflow discharge coefficient (A) and the probability of exceedance (P,%)

Table 2.

The probability of exceedance P (%)	0.1	1	3	5	10	25
Mudflow discharge coefficient A	2.4	1.0	0.7	0.6	0.5	0.3

Using the relationships (1) and (2), we calculated the erosion-washout coefficient for active tributaries of the erosion-destructive flow type within the river catchment area of the Bostanlyk district. Additionally, the maximum peak discharge values for destructive flows with a 1% probability of exceedance were determined.

RESEARCH RESULTS

Innovative Design of an Elastic Debris Flow Regulatory Barrier. Natural anomalies, particularly debris flows, necessitate specialized engineering solutions for effective mitigation. As debris flows are among the most destructive natural phenomena, regulation measures must be directly aligned with their genesis and dynamics. Conventional rigid barriers often fail to redistribute dynamic forces or alter the flow regime on the impact surface. To address these limitations, a collaborative research effort has resulted in the development of an innovative elastic debris flow regulatory dam.

1. Structural Design and Geometry. The barrier is composed of multiple sections featuring triangular prisms of uniform height integrated into the bed of the flow channel. These prisms are positioned with their lateral sides in close proximity. The base height of the prisms increases progressively along the direction of the debris flow, effectively creating a "trampoline" (kick-jump) effect.

2. Functional Elements and Elasticity. The upper segment of the structure is oriented against the flow direction. It incorporates elastic cables stretched between the upper edges of the prisms, which are interconnected to form a unified network. The lateral cables are configured to create "pockets" between the edges, specifically designed to capture and decelerate the debris mass.

3. Technical Novelty. Unlike traditional barbed-wire or rigid structures, the novelty of this elastic barrier lies in its constructive configuration. By utilizing triangular prisms combined with uniform vertical stems placed within the debris flow layer, the structure ensures a smooth, non-linear reception of the impact. This allows for the gradual dissipation of kinetic energy and the redistribution of dynamic pressure, significantly increasing the structural resilience of the dam.

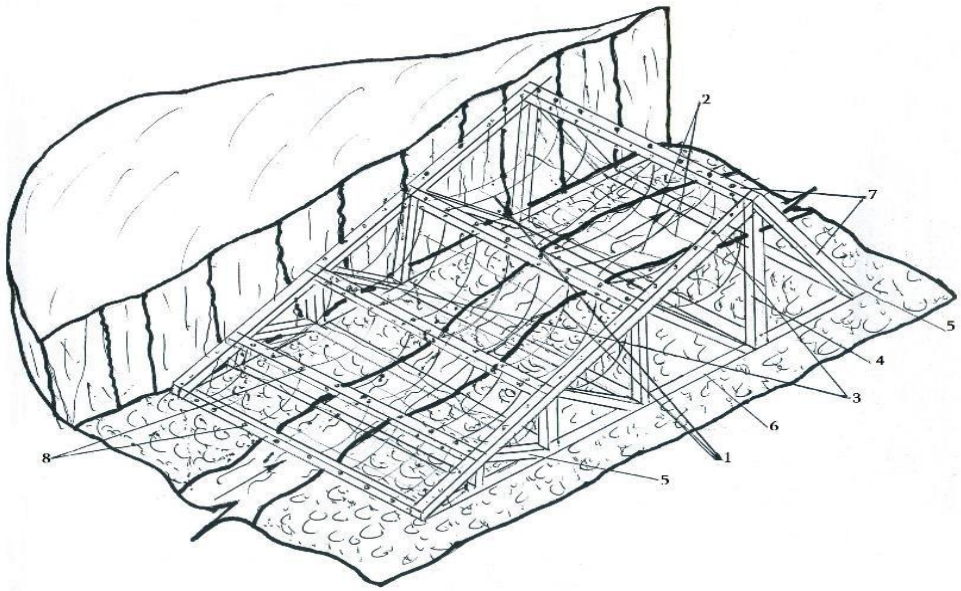


Figure 3. Flexible debris flow barriers

The proposed structure is designed in segmented sections to optimize force distribution. The impact-receiving surface is composed of high-tension cables, forming a curvilinear elastic mesh. Along the flow direction, the height of the prism supports increases progressively, functioning as a launch ramp (kick-jump) to dissipate kinetic energy. The cross-sectional dimensions and the overall length of the structure are determined based on the rheological properties, density, and impact force of the debris flow.

Figure 3. Legend and Component Description

The structural arrangement illustrated in Figure 3 consists of the following components:

1) *Longitudinal elastic cables:* Suspension elements that absorb tension along the flow axis.

2) *Transverse elastic cables:* Lateral cables that maintain structural integrity and form the mesh grid.

3) *Triangular prisms:* Primary deflectors that alter the flow trajectory.

4) *Triangular prism bases:* The foundational support for the deflectors.

5) *Prism base height:* Variable height segments that create the ramp effect.

6) *Prism anchors/grips:* Fixation points for the structural network.

7) *Attachment orifices:* Specialized openings for securing the mesh or secondary cables.

Mathematical Modeling of Dynamic Impact

The dynamic influence of the debris flow on the innovative regulatory structure is calculated using the following functional relationship:

$$P_1 = \frac{\gamma \omega V^2}{g} \sin\psi \, f(m) \text{ N/m}^2, \quad (3)$$

The dynamic impact of the debris flow on the innovative elastic structure is determined based on the following physical and rheological parameters:

γ – the volumetric weight (unit weight) of the debris flow mixture (N/m^3);

ω – the effective cross-sectional area of the flow (m^2);

V– the velocity of the flow (m/s);

φ– the internal friction angle of the debris material;

α – the gradient angle of the structure relative to its base (^{0});

f – the coefficient of internal friction, which is defined as follows:

$$\psi = tg^2(45^0 - \frac{\varphi}{2}), \quad (4)$$

Parameters of Flow Rheology and Interaction

h_0 – equivalent bonding depth (m)

H – flow depth (m)

a – a dimensionless coefficient defined by the relationship $(1 - h_0)\ \psi$;

f_m – a coefficient representing the rheological properties of the debris flow mixture.

$$f'_m = \frac{16 - \left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2}{\left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2} \quad (5)$$

The proposed structural advancement for debris flow mitigation is engineered as a high-strength steel-integrated spatial framework. To ensure localized stability under extreme hydrodynamic pressures, a system of isolated (point) foundations was strategically implemented. These foundations utilize B25 grade impermeable concrete (W8) formulated with Portland cement to withstand constant moisture exposure. Furthermore, advanced hydro-insulating coatings protect all structural surfaces in direct contact with the soil and fluvial seepage. The support architecture functions as a unified spatial system, specifically calibrated to absorb and redistribute both static dead loads and transient impulse forces generated by high-velocity mudflow events.

CONCLUSION

Based on the comprehensive analysis of debris flow dynamics and structural engineering solutions, the following conclusions were reached:

1. *Hydrological Vulnerability:* The 15-20% increase in daily precipitation intensity in Uzbekistan significantly raises the risk of "mixed-fed" mudflows, requiring a shift from rigid to flexible protection methodologies.
2. *Model Reliability:* The calculated discharge coefficients (ranging from 0.3 to 2.4 for P=25% to 0.1%) provide a calibrated baseline for engineering designs in the Bostanlyk district, ensuring that structures are resilient to 10-year and 100-year return period events.
3. *Structural Adaptation:* It is recommended to enhance flexible barrier designs by adopting a spatial system of triangular prisms with varying base heights. This modification creates a trampoline effect that redirects flow energy away from the foundation, thereby increasing structural longevity.
4. *Material Integrity:* For the implementation of these barriers in Uzbekistan's river basins, the use of point foundations with B25 grade concrete and W8 waterproofing is essential to withstand high filtration pressures and corrosive soil environments.
5. *Practical Application:* The proposed improvements to the elastic barrier design offer a cost-effective and structurally superior alternative to traditional concrete dams, providing a sustainable pathway for protecting the country's population and infrastructure.

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